Shock-Wave and Material-Properties Experiments Using the Atlas Pulsed-Power Machine

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The Atlas facility built by LANL is the worlds first, and only, laboratory system designed specifically to provide pulsed-power-driven hydrodynamics capability for shock-wave physics, materials properties, instability, and hydrodynamics experiments in converging geometry. Constructed in 2000 and commissioned in August 2001, Atlas is a 24-MJ, high-performance capacitor bank capable of delivering up to 30 MA with a current rise time of 5–6 µs. Atlas completed its first year of physics experiments in October 2002, using ultra-high-precision magnetically imploded, cylindrical liners to reliably and reproducibly convert electrical energy to hydrodynamic energy in targets whose volume is many cubic centimeters. Multiview (transverse and axial) radiography, laser-illuminated shadowgraphy, and VISAR measurements of liner and target surface motion, in addition to electrical diagnostics, provide a detailed description of the behavior of the experimental package. In the first year, material-damage and -failure experiments, dynamic-friction experiments, and a family of converging-shock experiments were conducted in addition to a detailed series of liner-implosion-characterization experiments. These experiments will continue, and an additional experimental series will be added in the future to evaluate material strength at very high rates of strain, ejecta formation from surfaces, and instability growth at interfaces.

Ultra-high-precision cylindrical liners imploded with pulsed-power techniques have been applied to a variety of interesting questions broadly addressing the properties and behavior of condensed matter and plasmas. Generally, these topics fall into three categories:

(1) the properties of condensed matter at the extremes of pressure, temperature, and energy density;

(2) the hydrodynamic behavior of imploding systems; and

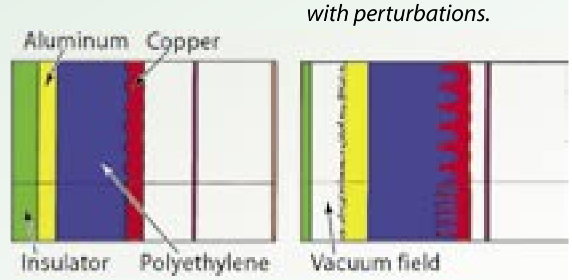
(3) the properties and behavior of dense plasmas.

In the first category, pulsed-power-driven liner experiments can explore the EOS of materials and phase transitions under single-shock (Hugoniot) conditions at higher shock pressures than those attainable by two-stage gas-gun/flyer-plate techniques. Magnetic drive offers shockless compression [1,2,3] that can drive materials to states not accessible through single-shock processes and to strains and strain rates far exceeding those available from other shockless techniques.

In the category of implosion hydrodynamics, liner-driven techniques are excellent for exploring

- instability growth in materials displaying full strength and in strengthless materials;
- the behavior of materials at interfaces (friction); and
- hydrodynamic flows in complex geometries.

Figure 1. Multilayer liner with perturbations.



In the third category, Atlas can produce plasmas in which the ion and electron physics are strongly coupled—where little experimental data are available. For the initial Atlas experiments, material strength and failure (spall), interfacial dynamics (friction), and complex hydrodynamic flow experiments were selected.

Material Properties

Pulsed-power-driven liners permit the study of strength of (and ultimately the failure of) materials under extremes of strain and the rate of strain. Because of cylindrical convergence, the inner surface of an imploding Atlas liner reaches strains exceeding 200% at strain rates of 10^4 to 10^6 per second. By proper choice of liner designs (e.g., a high-conductivity aluminum armature surrounding a thin cylinder of the material of interest), the test sample can be isolated from the effects of the drive (including magnetic fields and ohmic heating), and the acceleration can be applied in a way that ensures that the sample material is not shocked. A third layer, intermediate between liner and sample, can further isolate the sample from processes happening in the liner. This also allows additional control of the pressure history applied to the target. (Barns *et al.* pioneered such techniques with high explosives in 1974.[4]) For Atlas-based studies of material strength, a "three-layer liner" (Figure 1) has been designed by a joint LANL/VNIIEF team, including the All-Russia Scientific Research Institute of Experimental Physics (at Arzamas-16). The system employs an aluminum, current-carrying liner; a polyethylene intermediate layer; and a copper sample. Perturbations up to a hundred microns in amplitude and a few millimeters in wavelength are preformed (machined) into the outer surface of the copper sample. The perturbations can be detected by radiography before and during acceleration and are predicted to grow in amplitude by a factor of 2 to 8 during approximately 8 μs of drive (Figure 2).

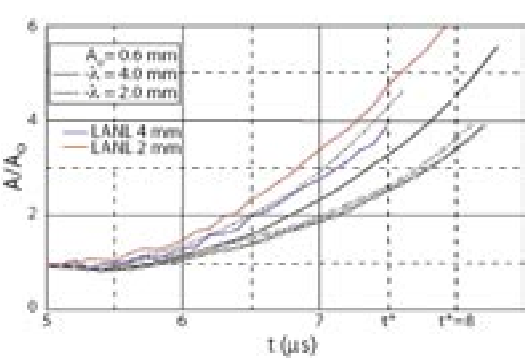


Figure 2. Perturbation growth for three-layer liners. A/A_O is the amplitude ratio.

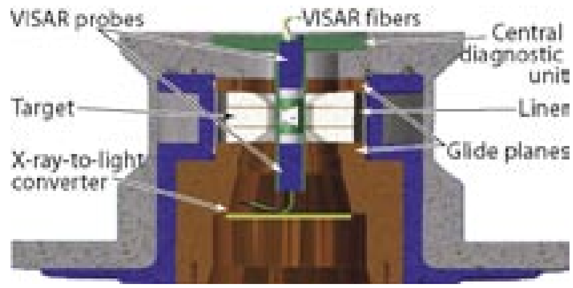


Figure 3. Atlas spall experiment.

While material-strength parameters can be deduced directly from the perturbation growth, the growth rates alone are sufficient to distinguish between several material models and among different computational techniques.

Liner implosions also offer unique opportunities for studying material failure (ultimate strength) at very high strain rates (in shocks) and at pressures that range from below the failure threshold to pressures many times that threshold. One convenient and familiar geometry for studying failure is the interacting shock geometry leading to "spall." Implemented in cylindrical geometry, the experiment is described in Figure 3. A series of four Atlas experiments have been conducted using a specially characterized, grain-oriented aluminum target material (driven by an identical aluminum liner) at shock pressures of 40–110 kbar. With these parameters, the tension in the sample ranges from that producing incipient spall to parameters where the sample clearly fails. Material behavior is diagnosed by monitoring the (inner) free surface velocity using VISAR. Figure 4 shows VISAR measurements of inner-surface velocity at two points, including shock breakout; the "pull back" as material is placed in tension; and the ringing after material failure. From peak velocity and velocity at failure, a spall strength can be found using established analysis techniques. In addition to VISAR, both transverse and longitudinal radiography is used to image the formation of the spall layer. Postfailure metallurgy provides important information about the behavior of the material during a spallation event. The controllability of pulsed-power-driven liners allows recovery of both native material and, in some cases, even the spalled material for post-event analysis—this is a significant advantage.

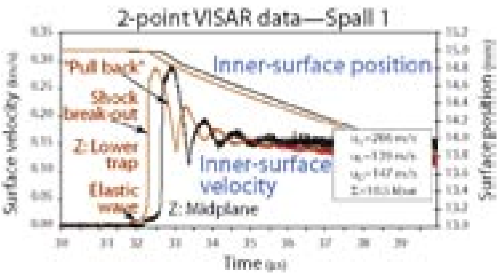


Figure 4. VISAR measurement of a spall experiment.

Implosion Hydrodynamics

Cartesian geometry is traditionally used to explore material properties; these studies of converging, liner-driven geometry represent an extension of those traditional methods. Symmetrical, radially imploding geometries can be readily studied by numerical simulation. Experimental data from configurations that are readily definable and calculable, but for which analytic solutions are not available, are important in benchmarking (both old and new) hydrodynamic (hydro) codes. The five-shot Atlas Hydro-Features (HF) series [preceded by the four-shot Near-Term Liner Experiments[5] (NTLX) series] began the process of gathering such data and demonstrated a sophisticated suite of experimental diagnostics for liner-driven experiments. Both HF and NTLX series employed a high-precision, shocklessly accelerated aluminum liner that drove a symmetrical cylindrically converging shock in a tin shock receiver. Tin melts at relatively low shock pressure; in the HF and NTLX experiment series, the shocked tin is a strength-free liquid. The converging shock emerges from the tin into a lower-density, optically transparent medium (acrylic or water) where its motion is characterized by two diagnostics simultaneously (Figure 5). A two-pass, axially directed, laser-illuminated shadowgraph records the change in refractive index and opacity of the material during passage of the shock, and a multiframe axially directed x-ray radiograph (Figure 6) records the change in material density as the shock moves through the material. Because of radial convergence, the shock speed should increase slightly as the shock approaches the axis, and the shock should reflect from the axis and expand uniformly through the once-shocked medium. Simulating the reflected shock is nontrivial, and the Atlas data constitutes nearly the only experimental data with high enough fidelity and precision to challenge the computational codes.

The next most challenging configuration for the simulation tools is where the symmetrical shock in the receiver emerges asymmetrically into the inner medium. This is accomplished in the experiment by introducing an offset between the axis of the inner medium and the axis of the shock receiver. The shadowgraph and radiographic diagnostics show that the convergence of the shock in the inner medium arrives off-axis as predicted. Taken together, these data constitute a significant test of both old and new simulation tools.

The imploding liner also presents opportunities for exploring the differential motion of material at an interface. Typically, experimental data on the behavior of material at "sliding" interfaces are limited to modest relative velocities and modest normal pressures. As relative velocities between the materials increase, one model predicts (supported by molecular-dynamic simulation) that the material at the interface melts and the presence of liquid at the interface reduces the effective frictional force. An experiment (Figure 7) has been designed to explore parameter space where the interfacial velocity varies from just below that for which the frictional force peaks and extends to values three to five times that value. The first of these experiments was conducted on Pegasus in 1998 and the second on Atlas during this first year of operation. For these experiments, a very thick, slow-moving liner impacts a cylindrical target—providing a supported shock of several microseconds duration. The target was configured as a sandwich of circular disks with a low-density (aluminum) disk between two high-density (tantalum) disks. The converging shocks generated when the liner impacts the target produce different particle velocities in the aluminum and tantalum disks—resulting in relative motion at the interfaces while simultaneously

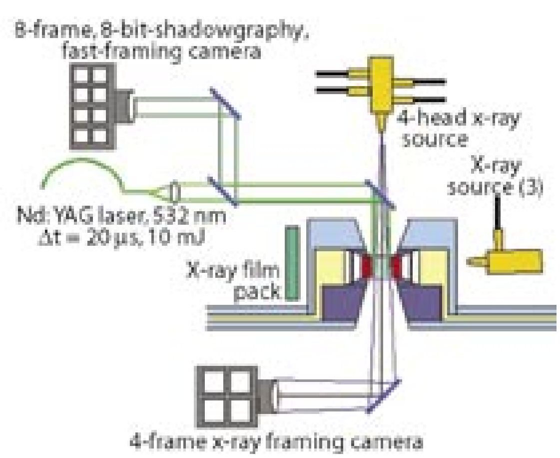


Figure 5. Diagnostics for HF experiments.

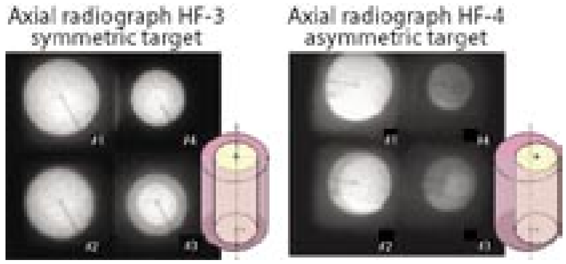


Figure 6. Radiographic data from symmetric and asymmetric targets. These are the third and fourth shots in the HF series.

pressurizing the target. Lead marker wires, 200 to 300 µm in diameter, are imbedded in the aluminum and radiographed in the transverse direction. Development of the boundary-layer motion is diagnosed by radiographying curvature and distortion of the wires. The experiment is performed as a function of shock strength (relative interfacial velocity), materials, and surface condition.

Conclusion

The development of economical, highly reliable, low-impedance capacitor banks coupled to high-precision, near-solid-density liners imploding at 5 to 20 km/s have made possible a wide variety of hydrodynamic experiments. The uniformity, controllability, and high liner velocities enable experiments not otherwise possible and represent a complement to lasers and nanosecond pulsed power used for radiation-driven experiments.

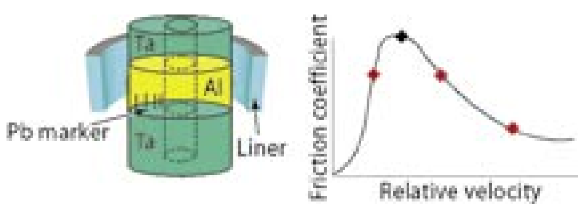


Figure 7. Atlas friction experiment.

References

1. J.R. Asay, C.A. Hall, K.G. Holland *et al.*, "Isentropic compression experiments on the Z accelerator," in *Proceedings of the Conference of the American Physical Society Topical Group on Shock Compression of Condensed Matter*, M.D. Furnish, L.C, Chhabildas, R.S. Hixson (Eds.), (American Institute of Physics, 2000), Vol. 505 pp. 1151–1154.
2. D.G. Tasker, C.M. Fowler, J.H. Goforth *et al.*, "Isentropic compression experiments using high explosive pulsed power," in *Proceedings of the Ninth International Conference on Megagauss Magnetic Fields Generation and Related Topics,* V.D. Selemir and L.N. Plyashkevich (Eds.), (VNIIEF, Sarov, Russia, to be published 2004).
3. A.M. Buyko, G.G. Ivanova, I.V. Morozova *et al.*, "Computation of electrically exploded opening switch for capacitor bank Atlas," in *Proceedings of the Ninth International Conference on Megagauss Magnetic Fields Generation and Related Topics,* V.D. Selemir and L.N. Plyashkevich (Eds.), (VNIIEF, Sarov, Russia, to be published 2004).
4. J.F. Barnes, P.J. Blewett, R.G. McQueen *et al.*, "Taylor instability in solids," *Journal of Applied Physics* **45**(2), 727 (1974).
5. P.J. Turchi, K. Alvey, C. Adams *et al.*, "Design, fabrication, and operation of a high energy liner implosion experiment at 16 megamperes," *IEEE Transactions on Plasma Science* **30**(5), 1777–1788 (2002).

Acknowledgment

This work was supported by the NNSA Office of Defense Programs. The Atlas experimental team includes operational functions provided by P-22 and Bechtel Nevada; diagnostic functions provided by P-22 and MST-10; precision-fabrication functions provided by MST-7; and design, simulation, and analysis functions provided by X-1, X-2, and X-4.

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